# The effect of photon counting detector blocking on centroiding for deep space optical communications

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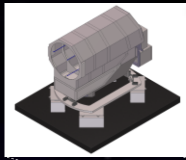
# Outline

- System overview
  - Pointing and tracking overview
  - Uplink beacon signal
  - Background subtraction
- Blocking model
  - Blocking compensation
  - Blocking impact on MSQ statistic
- Centroid performance results
  - Monte-Carlo simulation
  - Laboratory testing

# Deep-Space Optical Communications (DSOC)

Flight Laser Transceiver (FLT), 22 cm



Psyche Spacecraft (2022)

– ***OBJECTIVES:***

*Advance NASA's enhanced communication goals by:*

- *Demonstrating optical communications from deep space (> 2 AU) to validate:*
  - *Link acquisition and laser pointing control*
  - *High photon efficiency signaling*

1064 nm uplink

1550 nm downlink

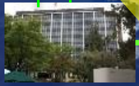
**Ground Laser Transmitter (GLT)**
**Table Mtn., CA**
**1m-OCTL Telescope**

**Ground Laser Receiver (GLR)**
**Palomar Mtn., CA**
**5m-dia. Hale Telescope**

**Deep Space Network (DSN)**

**Psyche Ops Center**

**DSOC Ops Ctr.**



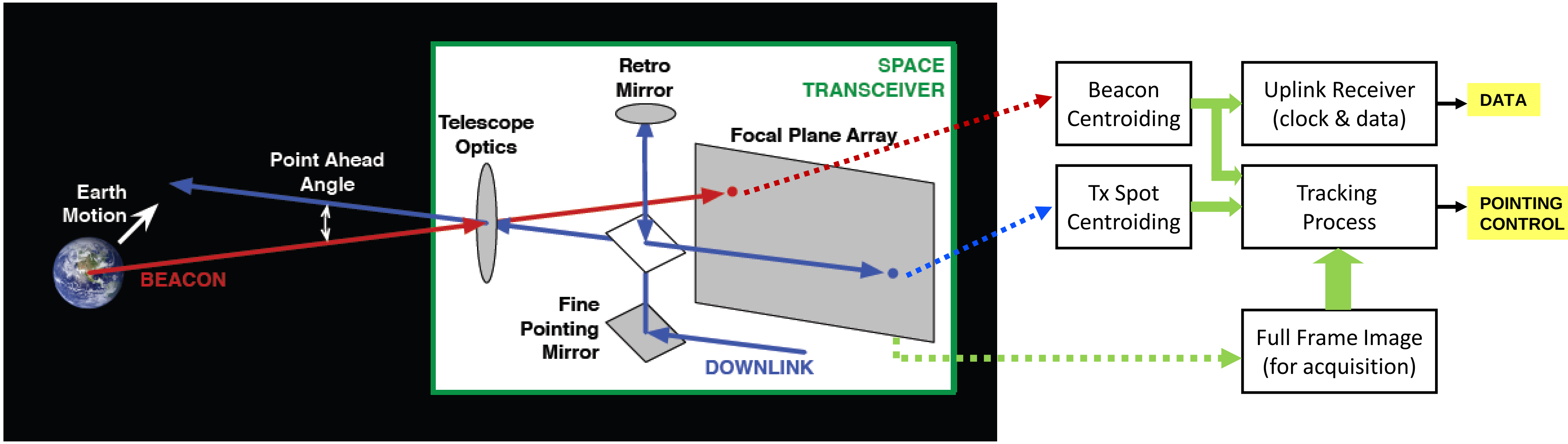
**See DSOC presentation by Abhijit Biswas**

**Tuesday Jan 30, 11:10-11:30 AM**
**Room 158**

**(Paper 10524-30)**

# Beacon-Assisted Pointing and Tracking






- **Uplink beacon provides reference pointing information without increasing mass of flight transceiver.**
- **Uplink signal position is estimated in order to**
  - **Adjust flight terminal platform attitude and calculate point-ahead angle for downlink transmission**
  - **Acquire and demodulate uplink data**
- **A single detector array reduces alignment errors and optical losses**
  - **Used to estimate location of dim laser beacon to point transmit beam to Earth ground receiver**
  - **Tracks angle of the transmit beam to confirm the point-ahead angle**
  - **Photon counting array has best combination of sensitivity and bandwidth**
- **Signal processing needed for simultaneous spatial acquisition, tracking, parameter estimation and data demodulation**

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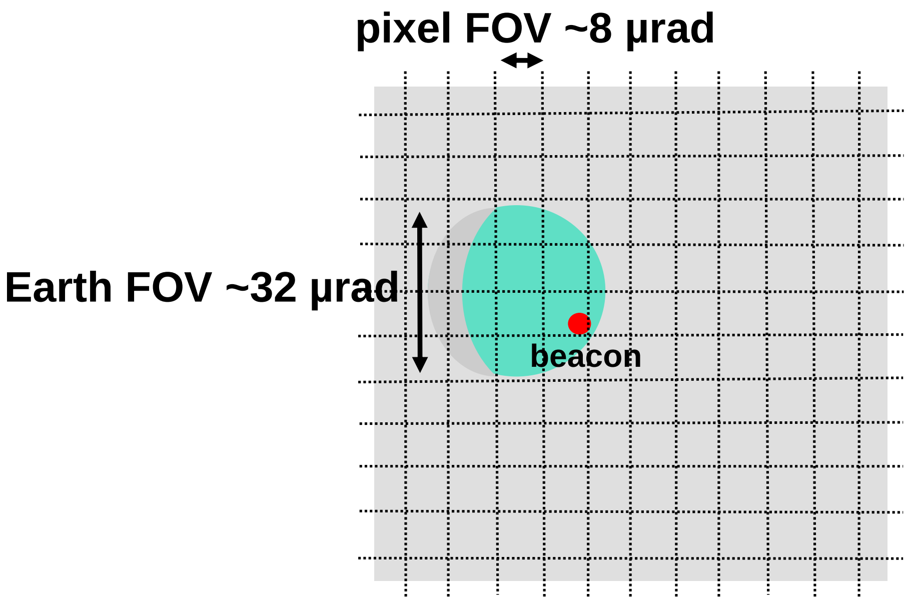
# Beacon Centroiding and Downlink Pointing

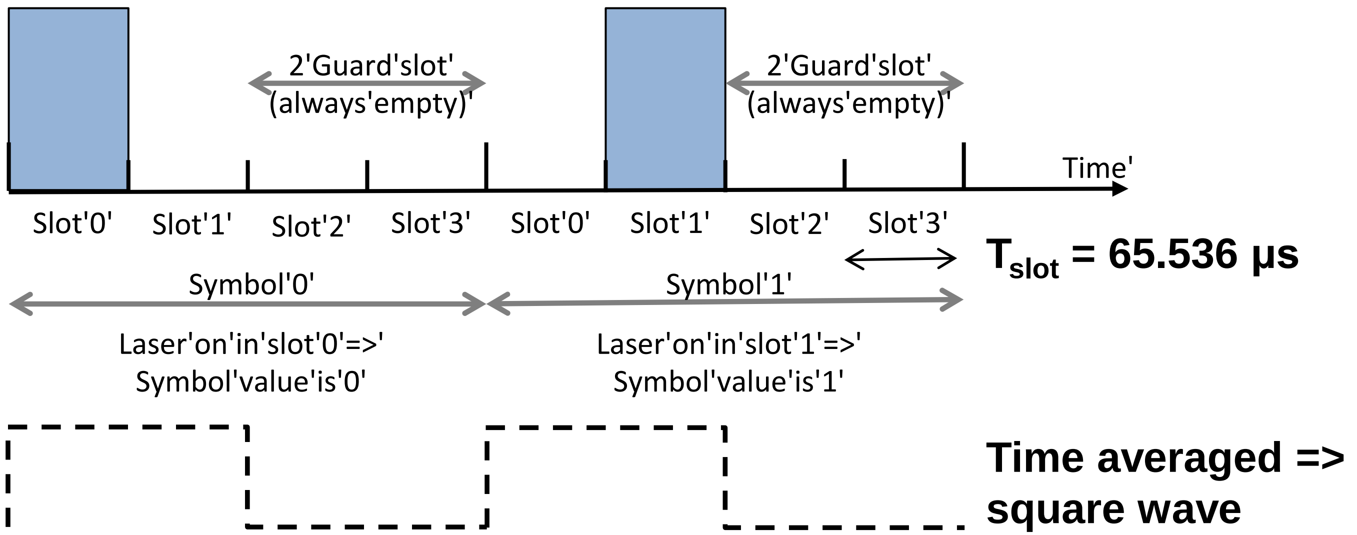
- Uplink beacon tracking error translates directly to downlink pointing error
- <1 µrad beacon centroiding accuracy needed
- Example case: Spacecraft at 2.7 AU




- Beacon irradiance in $pW/m^2$
- Earth radiance dominates beacon flux
- Beacon centroid biased towards Earth centroid
- We need subpixel beacon centroid accuracy, using currently available photon-counting cameras

# Uplink Signal Format

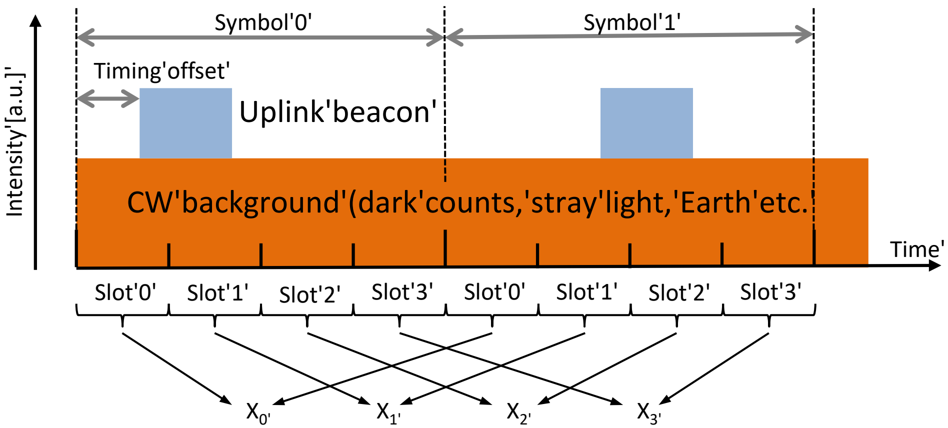
- **The DSOC uplink beacon uses a 2-PPM with 2 intersymbol guard time (ISGT) slots modulation**
- **This scheme provides a low rate command channel**




- **50% average duty cycle beacon is optimal for signal estimation**
- **Background subtraction is implemented using a pair of up-down counters offset by command channel slot width**

# Background subtraction

- **The modified square law (MSQ) statistic is calculated for each pixel on the array using N symbols (N=64 for 60Hz update rate).**




$$X_m = \sum_{i=0}^{N-1} x_{corr}(x_{4i+m}), \qquad m \in \{0,1,2,3\},$$

$$\begin{aligned} U &= X_0 + X_1 - X_2 - X_3, \\ V &= X_0 - X_1 - X_2 + X_3, \\ S &= X_0 + X_1 + X_2 + X_3. \end{aligned}$$

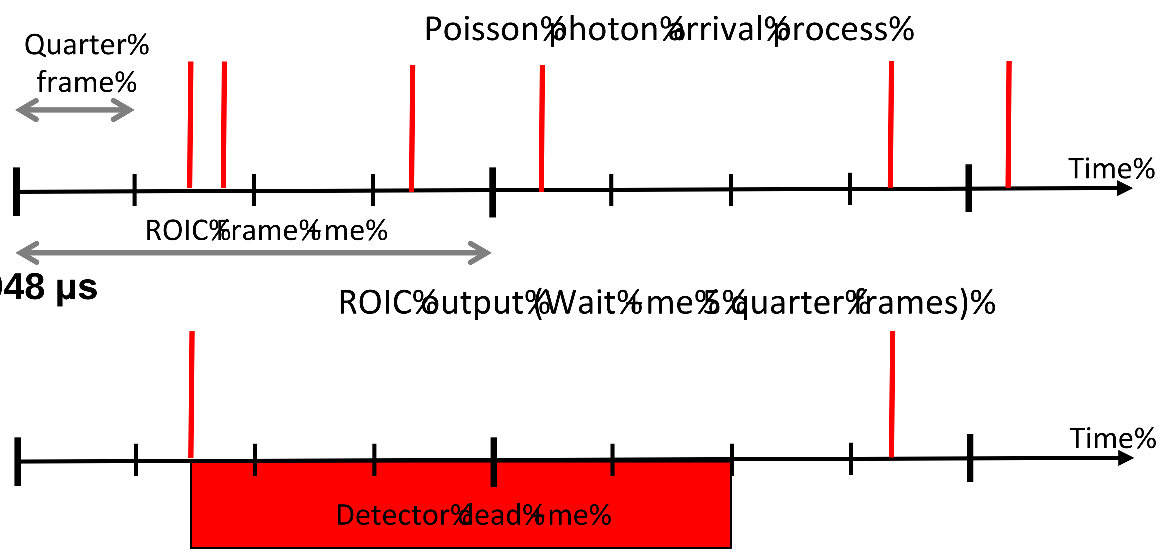
$$W = U^2 + V^2 - 2S.$$

- **The MSQ statistic, W, does not depend on the background level and is proportional to the modulated signal level squared.**

- **The centroid estimate is calculated using the MSQ statistic in a small subwindow (e.g., 2x2 or 3x3 pixels).**

# Detector/ROIC Blocking Model

- ***Blocking*** **limits maximum detectable counts, and comprises two effects**
  - **Detector dead time – After a photon detection event the detector is held in an off-state for a set amount of time to limit afterpulsing**
  - **ROIC frame rate/single photon detection limit – at most one count per frame recorded**
- **The dead/wait time on the PCC ROIC is discretized in units of quarter ROIC frames.**
  - **The nominal wait time is 5 quarter frames:**




**$T_{\text{ROIC frame}}$ = 2.048 μs**

- **Blocking manifest itself as a nonlinear response at high count rates and is exacerbated by pulsed or modulated signals**

# Blocking compensation

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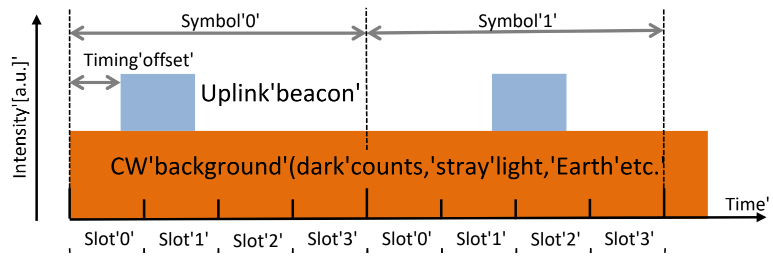
- **Using straight forward statistics, the effect of blocking can be compensated for.**
- **The most simple form is:** $\lambda_{true} = -\ln(1 - \lambda_{obs}).$

- **For the DSOC PCC+ROIC setup, this translates to:**

$$\lambda_{true} = -\ln(1 - \lambda_{obs,adj}) = -\ln\left(1 - \frac{x}{n - x(N_{wait} - 1)}\right).$$

**where *x* is the number of observed counts in *n* quarter frames.**



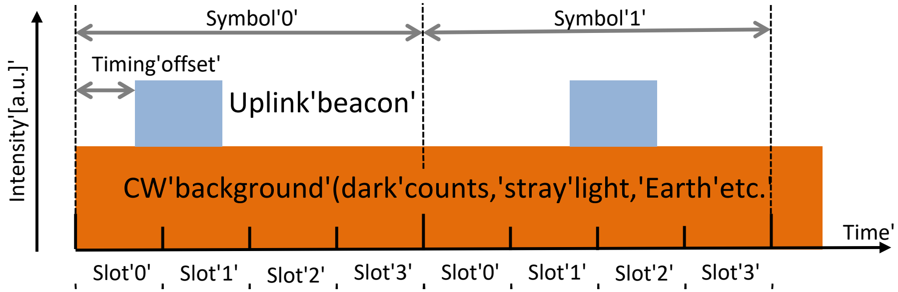

- **However, due to the modulated signal, the blocking compensation has to be done on a slot-by-slot basis (i.e., on the readout FPGA). Thus, the blocking compensation is implemented using a lookup table using the correction:**

$$x_{corr}(x) = floor\left(n_{slot}\left(-\ln\left(1 - \frac{x}{n_{slot} - x(N_{wait} - 1)}\right)\right)\right),$$

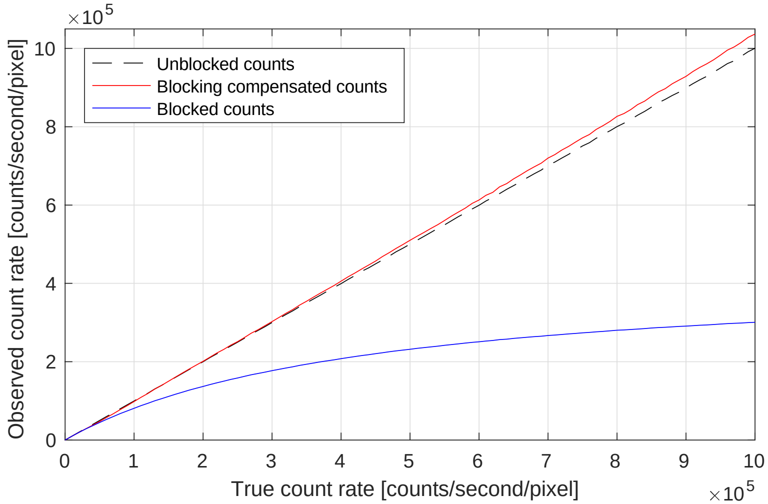
**where $x_{corr}$ is the corrected number of counts in one slot and $n_{slot}$ is the number of quarter frames in a slot ($n_{slot}$ = 128).**

# Blocking compensation cont.

- **The blocking compensation scheme assumes the count rate is constant over the integration time (one slot).**
  - **This assumption is reasonable in tracking mode where the timing offset is actively minimized**
  - **In acquisition mode the timing offset is unknown (1/2 slot worst case)**




- **Blocking compensation linearizes the detector response**
  - **This helps the underlying algorithms (e.g., the MSQ statistic) which were derived assuming a linear response**
  - **It does not "create" signal where there was none. I.e., the noise is also amplified.**




- **The limited integration time and restriction to integer numbers causes a small overestimation of the corrected counts.**

# Impact of Blocking on MSQ statistic

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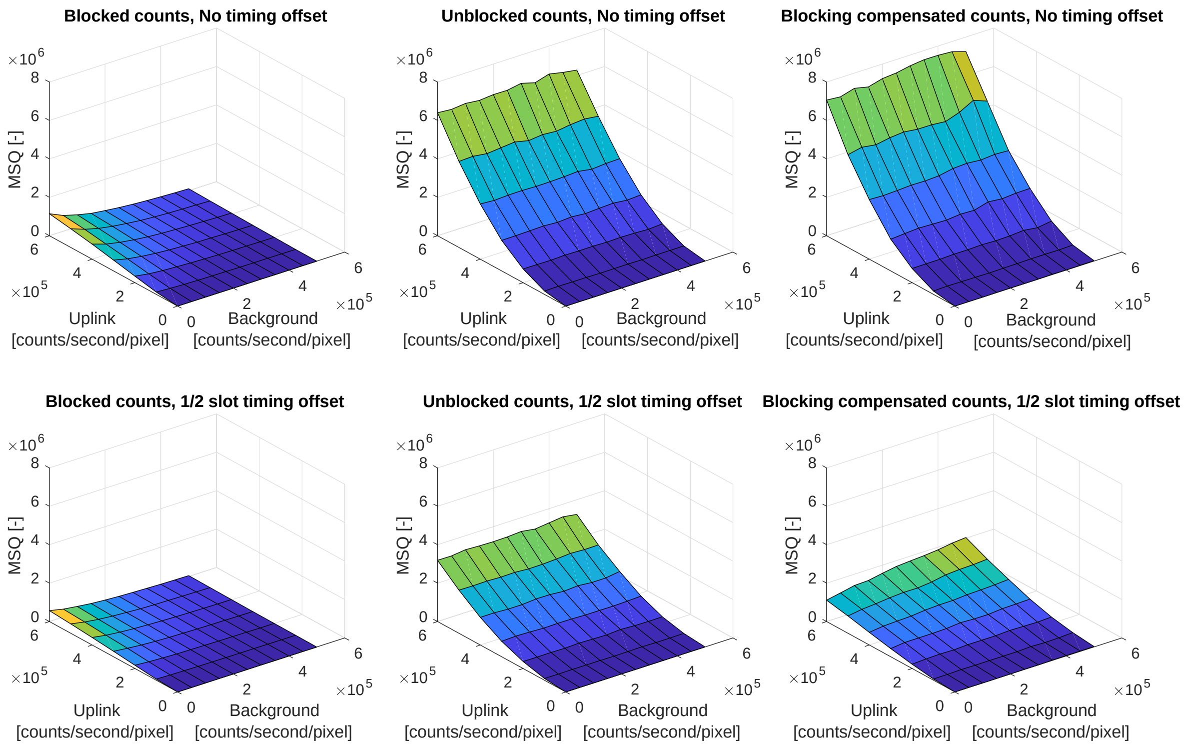
**Monte Carlo simulations the impact of blocking on the MSQ statistic under relevant uplink and background count rates**




**No timing offset: blocking compensation works well**

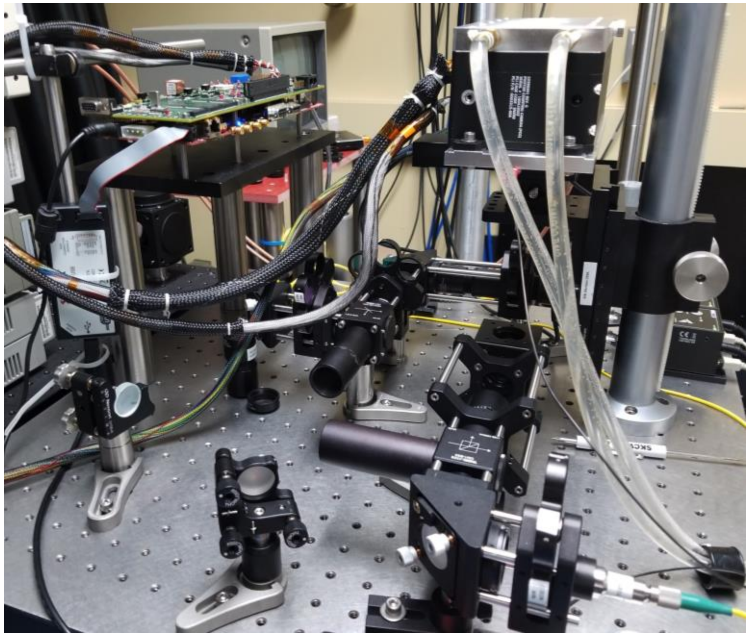
**Worst case timing offset: As expected blocking compensation is not ideal, but meets Acquisition mode requirements**

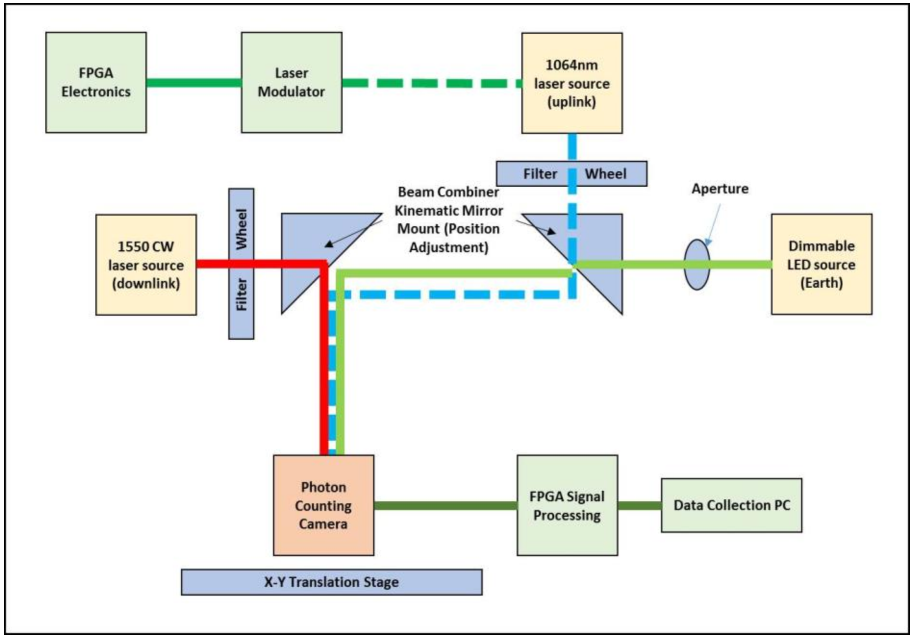
- **Contrary to previous assumptions, blocking compensation is important, even in the absence of background.**

# Performance testing

**Centroiding performance was tested using two models:**

- **A high fidelity Monte Carlo code, simulating the detector array, ROIC, and readout FPGA in software**
- **A Photon Counting Camera test bed for detector an algorithm testing under realistic conditions**
  - **Including separate 1064nm uplink and 1550nm downlink sources, variable background models**
  - **PCC mounted on motorized precision XY translation stage for accurate (relative) movements.**



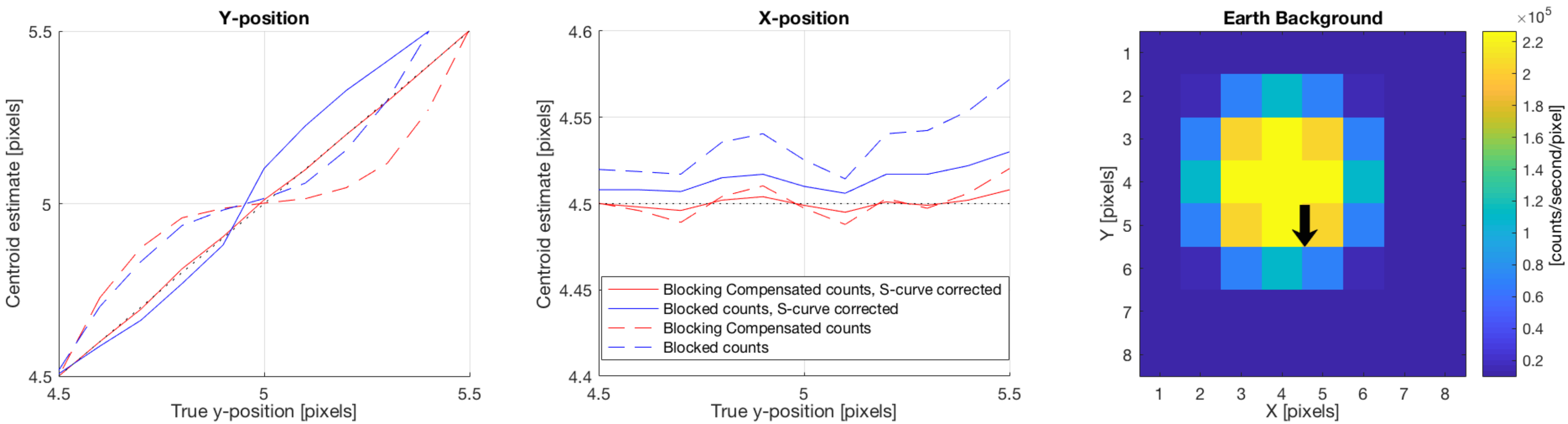


# Performance testing cont.

- A standardized test case was constructed and used as the baseline for testing.

- This test case represent the worst case conditions for the DSOC mission:
  - 2.7 AU Earth-Spacecraft distance
  - Fully illuminated Earth background (0.0087 W/(cm2·sr·µm)) with a 1 nm bandpass filter
  - Low beacon power at detector (~100 fW average power)
  - 30% detector efficiency assuming 100% fill factor
  - 10000 counts/second/pixel Dark counts and Stray light
  - Centroid update rate 59.6 Hz (64 symbols integration time)
  - 5 quarter frames blocking time.

# Monte Carlo Centroid tests

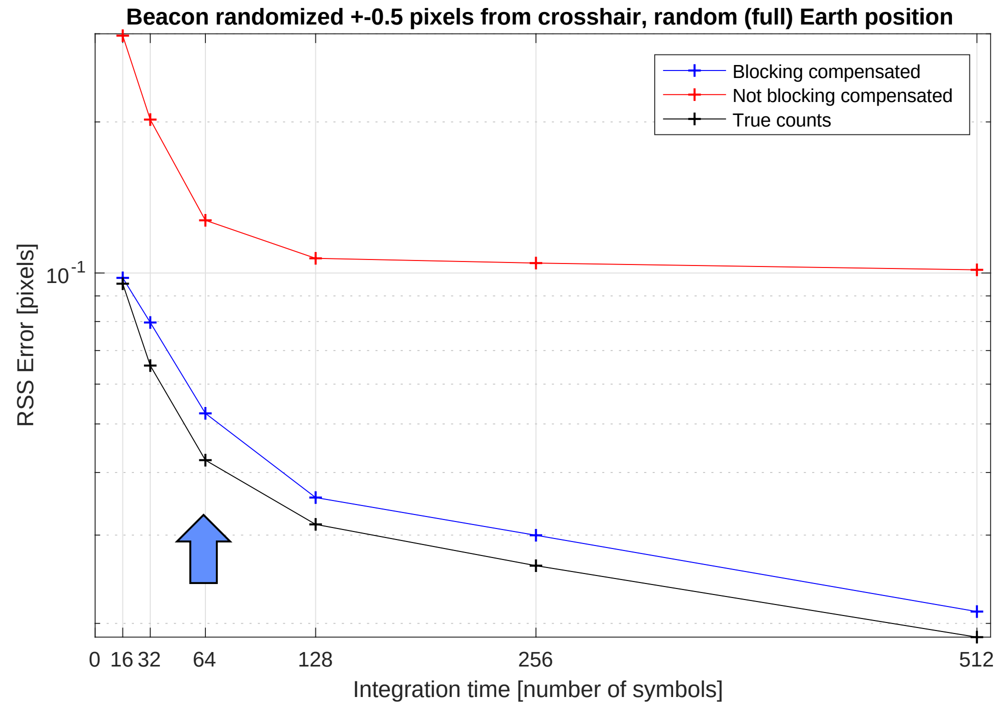



- **Using the 2.7 AU test case the uplink beacon centroid is calculated for various Y-position on a full Earth background (indicated by the arrow), using a 3x3 subwindow.**
- **Using the blocking compensated counts, the Y-centroid estimate shows a symmetric S-curve (red dashed) which is easily corrected for (red solid).**
- **Without blocking compensation, the X- and Y-centroid estimates show significant asymmetry (blue dashed). This is due to the background dependence of the MSQ statistic resulting in a background dependent bias. This bias can not be corrected for (blue solid).**
- **The integration time here is 50x64 symbols (0.84s) to highlight bias instead of noise.**

# Monte Carlo Centroid tests cont.



- The Monte Carlo code was used for a wide range of parametric studies
- Here the RSS error is shown as a function of the integration time
    - (64 symbols nominal)
- The results for the blocking compensated counts follow the true counts with a small offset:
    - The RSS error decreases with longer integration time.
- However, the RSS error for the non-blocking compensated counts level out at ~0.1 pixels RSS error due to the limit imposed by bias error.

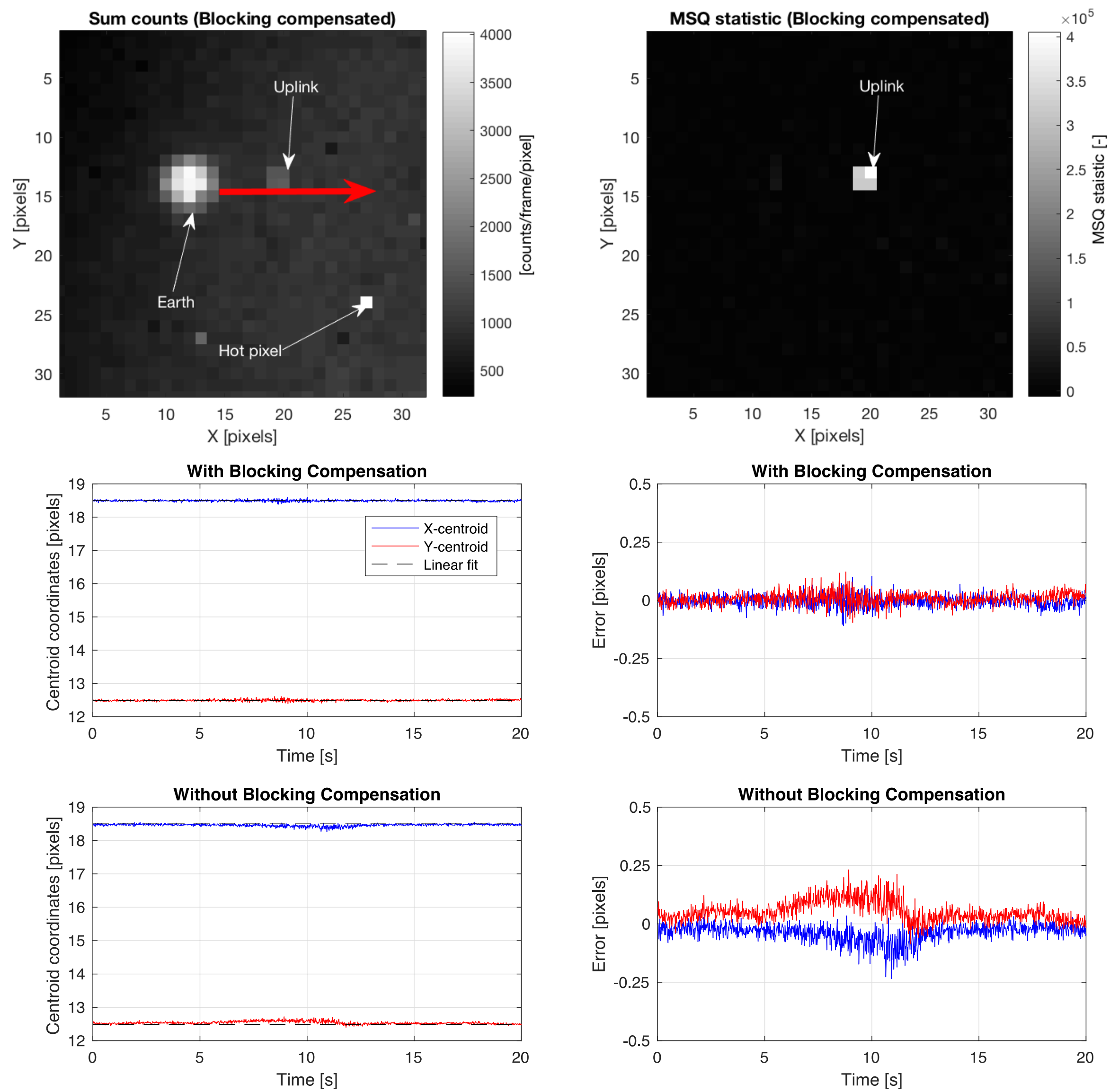



- 2.7 AU test case
- 2x2 centroiding subwindow
- S-curve correction applied
- No timing offset
- RSS = sqrt($RMS_X^2$ + $RMS_Y^2$)

# Laboratory Centroid test

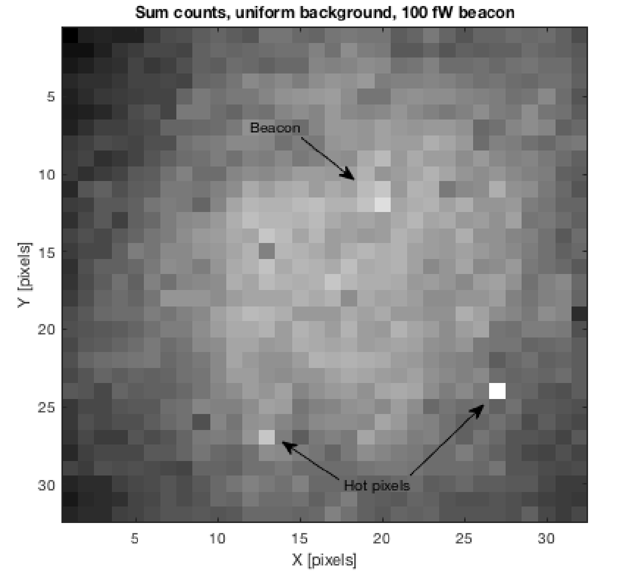


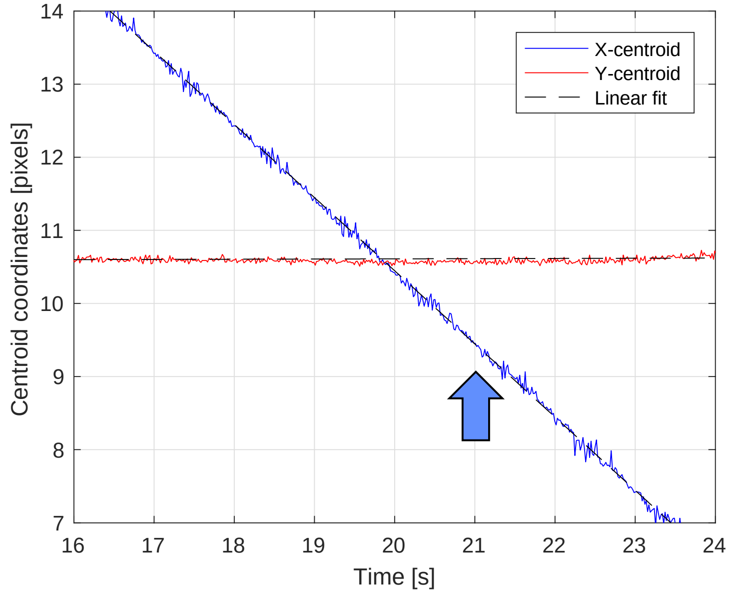
- **In the laboratory test setup it is easier to move the Earth over a stationary uplink spot**
- **Here we show the X- and Y-centroid estimates for two separate Earth sweeps, with, and without blocking compensation enabled.**
- **Signal and background levels are consistent with the 2.7AU test case.**
- **With blocking compensation enabled the centroid estimate jitter increases with the Earth present, but the mean position stays constant (no bias)**
- **Without blocking compensation, significant bias is apparent, as expected.**

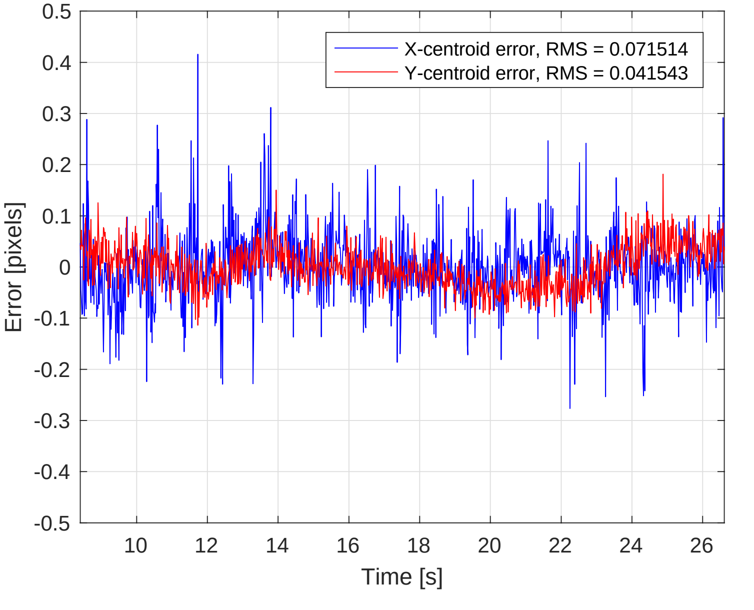


# Laboratory Centroid test cont.

- Lacking an absolute beacon position reference, linear sweeps of the beacon spot over a uniform background at a constant rate gives a relative reference.
- A linear fit to the X and Y centroid estimates thus acts as the “true” position.
- X- and Y-centroid errors are 0.07 and 0.04 pixel RMS respectively over the entire sweep.
- In tracking mode we would choose to operate over a 4-pixel crosshair where jitter is minimized.



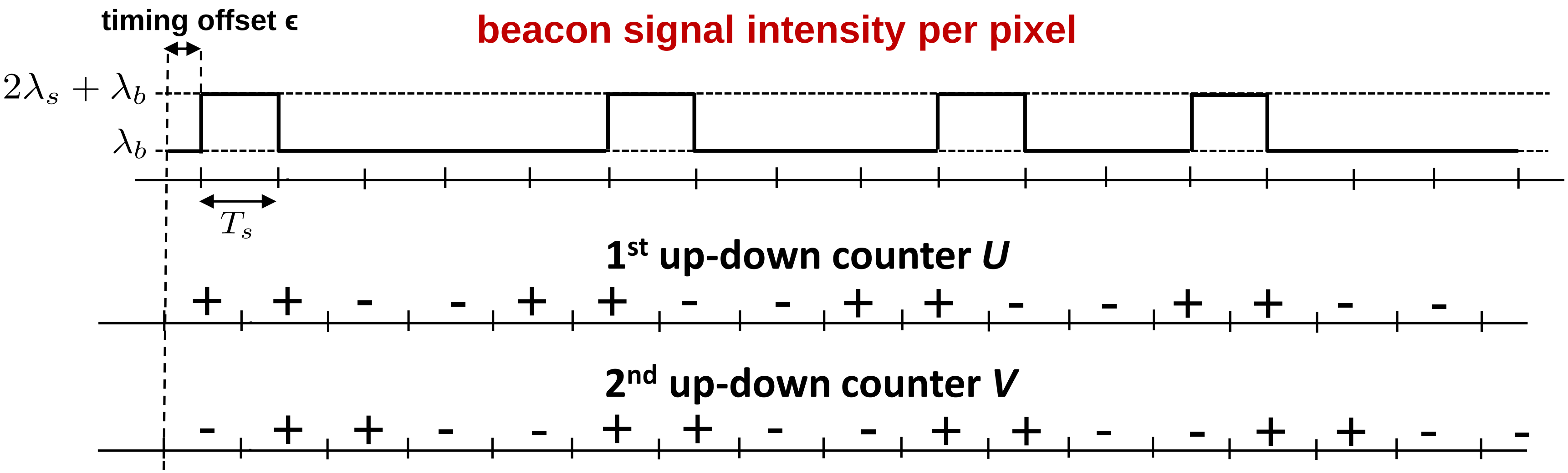
# Summary

- Developed a blocking compensation model and implemented blocking compensation in PCC readout electronics (FPGA)
- Using Monte Carlo simulations and a laboratory test bed we showed that:
  - Blocking breaks the background independence of the MSQ statistic, leading to significant centroiding errors (bias)
  - Blocking compensated counts closely follow the True counts, with a small noise penalty associated with the discarding of data
  - Using the blocking compensation, combined with S-curve correction, leads to centroid estimates that are linear with displacement and free of bias.
  - Uplink beacon centroid jitter is <1 μrad even under worst case dynamic conditions
  - In Tracking mode, near 4 pixel crosshair, uplink beacon jitter is <0.5 μrad
- The blocking compensation algorithm degrades with timing offset
  - Only matters in Acquisition mode where centroiding accuracy is secondary.

# Backup

# Up-down Counter Statistics

- **Up-down counters alternately increment and decrement pixel counts at beacon frequency**




- **The up-down counter (UDC) outputs $U$ and $V$ have mean and variance**

*no dependence on background*

$$E[U] = 4N(1-\epsilon)\lambda_s T_s, \qquad Var[U] = 4N(\lambda_b + \lambda_s)T_s$$

$$E[V] = 4N\epsilon\lambda_s T_s, \qquad Var[V] = 4N(\lambda_b + \lambda_s)T_s$$

**where $N$ is the number of beacon cycles, ε is the slot timing offset, and $T_s$ is the slot time.**

- **Modified square law statistic $W^* = U^2 + V^2 - 2S$, where $S$ is up-counts, enables signal detection without phase synchronization, and has expected value that does not depend upon background.**